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Observations in the area of flank land wear for carbide inserts

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OBSERVATIONS IN THE AREA OF FLANK LAND WEAR FOR CARBIDE INSERTS

by
John Albert Young

A Thesis

Presented to the Graduate Faculty

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date

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INTRODUCTION

Objectives and Scope

The original idea for this thesis was obtained from work done by Takeyama, Muria, and Usui,[6] in their study of the wear process of carbide tools. They found that the curves of land wear versus time for carbide tools consisted of two distinct straight line portions when plotted on log-log paper. They defined the point at which the two portions of the plot intersect, as the "critical point" of wear.

The objective of this thesis was to study this "critical point" and in doing so, two other objectives in the area of tool wear were studied. One was to study the phenomena of diameter size change, especially where the starting diameter was greater than the diameter at the finish of the cut. The other area encountered was that of plastic deformation on the flank of the tool, especially in connection with the size change of the diameter.

In an attempt to meet these objectives, a wide range of areas was investigated. The tests covered a wide range of speeds and feeds, with emphasis on roughing cuts. The wear characteristics of the tools were tested to a point usually sufficiently greater than the .030 in. land wear specified as the accepted limit for tool wear during roughing cuts.

Also, simultaneous measurements were made of surface finish, tool forces, diameter size change, and land wear, in trying to find relationships between them in meeting the objectives of the study.

The importance of making observations over such a wide range was emphasized by the fact that the original general testing led to a concentration on a particular area, after initial results were analyzed.

Technical Principles

In deciding what speeds to run the tests, reference was made to Le Grand's work,[4] who found that the tool life for 4340 steel was best at 400 SFPM. He also stated that tool life was short at 600 SFPM. Therefore, it was decided to use a range of 300-500 SFPM.

Reference has already been made to Takeyama et.al.,[6] but now follows a more thorough discussion of their work in the area of the wear process of carbide tools. From their work with carbide tools on steel and cast iron, they concluded that the land wear vs. time plots should be made on log-log paper. In doing this they obtained a plot which consisted of two straight line portions. Also, they referred to the point where the slope of the initial straight line changed to the slope of the second straight line portion as the "critical point."

In their tests on Ni-CR-Mo steel, Takeyama et. al.[6] reported that the "critical point" for four S-1 carbide tools varied from

0.0158 to 0.0177 inches. Also, they concluded that the second stage of the wear was independent of speed, after having tested under a variety of cutting conditions. They agreed with the fact that the "critical point" varied as one varied the workpiece material.

The reason that Takeyama et.al[6] gave for this onset of accelerated wear, after the "critical point" was reached, was that it was caused by the decreased wear resistance of the tool at the increasing temperatures. However, Shaw and Dirke[5] pointed out that the hardness of the carbide tools at these elevated temperatures was greater than that of high speed steel at room temperature. Therefore, since Takeyama et. al. produced no proof of their theory, it is not accepted, especially in the light of these other findings.

Takeyama et. al. conclude from their test that the slope of the first stage of wear directly influenced by the type of land wear, and that it is usually about 1.8. And, since they stated that the second stage of the wear was independent of cutting speed, they suggested that it might be possible to rank order rate the S series of carbides at the first stage of wear.

Another conclusion they made, that leads to the next part of the discussion, was the fact that in this initial stage of wear, the wear process was greatly affected by an abrasive type of wear. This abrasive type of wear on the flank below the cutting edge is one of the more prominent types of tool failure, as can be seen by reference to such work as O. W. Boston's.[3,2] The American

Standard's bulletin on "Life Tests for Single Point Tools of Sintered Carbide,"[8] says the following about this flank wear: "A careful study of the wear of these tools has resulted in the practice of running a tool until the wear on the flank averages about 0.030 in. as measured from the original cutting edge."

In discussing ways of evaluating tool life, Boston[3] gives a list of seven commonly used techniques. Among them is one that is pertinent to this study. He says, "determine the time of failure as indicated by an increase in diameter, or loss in depth of cut, as the tool end flank is abraded." This refers to the loss in diameter size caused by tool wear, since the cutting edge of the tool will be at a different point if a constant dial setting is used. Also, Boston being an advocate of this technique for determining tool wear, he suggests that the diameter of the work will increase with time and wear.

In outlining the technical principles here, it is assumed that the reader has a basic knowledge of the material on tool wear, such as F. W. Taylor,[7] M. F. Merchant,[3] A. O. Schmidt,[3] and many others. Another thing that should be kept in mind when discussing tool wear is the economics of the whole area. A good background in this area is presented by W. W. Gilbert.[3] Another text that is very valuable in the area of tool wear is "An Evaluation of the Present Understanding of Metal Cutting."[1] This is especially helpful in trying to correlate the work done in the field of metal cutting. Special note should be made of the "Metal

Cutting Bibliography, 1943-1956,"[9] which is a valuable aid in the literature search for this field.

PROCEDURE

Apparatus

LeBland Engine Lathe - 16" Heavy Duty
20 - ½" swing
7'6" bed length
20 horsepower

Dynamometer - Shaw, Smith and Associates.
Horizontal and Vertical Forces

Twin - Viso Recorder -- Sanborn Company
Two Channel
Recording Paper

Profilometer - Hand Trace

Scales:	3	micro-inches	Increment	Readings	.1
	10	"	"	"	.5
	30	"	"	"	1
	100	"	"	"	5
	300	"	"	"	10
	1000	"	"	"	50

Dial Indicator
Scale division - .0005

Toolmaker's Microscope - Bausch and Lomb Stereomicroscope
Lens   Scale Division - .0001
20x   2x and .5x attachment lens
Eyepieces

Optical Comparator and Measuring Machine - Jones and Lamson
Lens - 50x
Horizontal and Vertical Micrometer Scales
Scale Divisions - Horizontal .0001, Vertical .0001

Machinibility Computer - General Electric

Micrometers
2" - 7"
Scale Divisions - .001

Work Material:

SAE 4340 HRS, Quenched and Tempered

Hardness -

Surface - 302 BHN

Cross Section - 285 core - 302 surface

Diameter - 7"

Length - 16'4" cut into 4 equal lengths

Average Cutting Length - 42"

Chemical Composition

C - .40
MN - .71
P - .011
S - .015
Si - .35
Ni - 1.80
CR - .83
Mo - 24

Tool Materials:

Carboloy Inserts

SQT-162U4	½ sq x 1/8 thick, 1/16 R., Tools #1-10. 370 Grade	
SQT-162U2	½ sq x 1/8 thick, 1/32 R., Tools #11, 13. 370 Grade	
SQP-162P2	½ sq x 1/8 thick, 1/32 R., Tools #12, 14. 370 Grade	

Tool Holders

SBPR-16 ,	0,	6,	11,	5,	15,	15,	0.
SBTR 16 ,	-5,	-5,	5,	5,	15,	15,	0.

METHOD OF TESTING

The following conditions were present in the testing procedure.

Material - SAE 4340 - constant

Depth of Cut - 0.100 in. - constant

Feed Range - .0144-.029 in./rev

Speeds - 270 and 394 RPM

SFPM Range - 308-511 SFPM

Cutting Conditions - Dry

The machinability computer was used to determine the approximate feeds and speeds that would give the desired tool life. Initially it was decided to do the testing under conditions similar to roughing cuts as opposed to finished cuts. On this basis then, with the speed range also determined on a realistic basis, a feed was determined that would give the tool approximately .030" land wear on one pass of the tool along the length of the bar (approximately 42 inches).

Thus, with the aid of the computer and a little experimenting, it was found that .0144 in/rev feed at a speed of 270 (500 SFPM) was a starting point. After that the surface feet were varied only by the diameter reduction until it reached about 350 SFPM, and then the speed was changed to 394 RPM so that the SFPM was again around 500 SFPM. Further diameter reductions reduced the surface feet to about 300 SFPM at a diameter of about three inches, which was the smallest diameter it was desirable to cut.

While surface feet were changing with the diameter reduction, the feed was being changed after every cut, covering the range of .0144 to .029 in/rev. Thus, a different tool edge was being used for every pass along the bar, except when the diameter became small it took two or three passes to obtain a land wear of .030 inches or more.

By running the tests in the range of 300 to 500 SFPM, and increasing the speed of the machine to obtain these surface feet, two sets of data were obtained from each bar, for the same feeds, at speeds that varied 10 or 15 SFPM. This was as close to identical that tests could be conducted with the speed variations available on the lathe.

Therefore, by cutting two bars, four sets of data were obtained for most of the speeds and feeds used. This was done to try and get sets of data run under similar conditions so that comparisons could be made and differences evaluated. In the initial tests, a total of 36 tool edges were run.

The next thing will be to discuss the details involved in testing each tool edge. In doing this, it was found that the tool should be run for a certain amount of time, then taken out and measured for tool wear; inserted; run again; measured; etc. The time was dependent on the speed and the feed of the individual cuts, and was varied so that approximately 8 or 10 readings were obtained for each tool edge. Also, while the tool was cutting the lathe dynamometer and the strain-gage recorder were operating, so that a recording of the horizontal and vertical forces on the tool were measured for each time interval.

The land wear was measured each time on the tool maker's microscope and the maximum wear was measured as opposed to an average. The maximum measured did not include grooves that were formed in the tool by metal caught between the tool and the work or that were formed by some other obvious action.

After a pass had been made over the length of the bar, the surface finish was recorded for each interval of cutting. Also, at this time the diameter at the beginning of each individual cut was measured as well as the diameter at the end of the cut; this is referring to measurements to show differences longitudinally and not just to check the depth of cut. That is, to see if there was any taper over the length of each interval along the bar.

This concluded the initial testing, and resulted in producing data showing land wear, surface finish, diameter differences, and horizontal and vertical tool forces, at different times for each of thirty-six tool edges. All of these tool edges were from the same type of tool, a Carboloy SQT-162U4, Grade 370, with an SBTR-16 tool holder.

After the data was analyzed, it was found that a few additional special tests should be run. The first of these was run the same as the initial test except that a dial indicator was clamped on the carriage of the lathe and placed against the back of the dynamometer tool holder. Then, the movement of the tool holder either toward or away from the work was recorded for each time interval for a set of four tool edges which were run at different feeds and surface speeds. The tools used here were the same as were used previously.

The next of the special tests was also run with the dial indicator and was the same as the initial tests except that the dynamometer was not used. In this case, a positive and a negative rake tool were used for the cutting. These tools were similar in all respects except that the one was positive and the other was negative. They were Carboloy SQT-162U2 tools, with SBTR-16 tool holder, and SQP-162P2 tool, with SBPR-16 tool holder. In running this test, the positive and negative tools were run at the same feeds and speeds for each set, except that the SFPM was different by the amount of the diameter reduction of one cut. The order of each set was reversed every time, so that any differences here could be separated. A total of five edges of each type of tool, both positive and negative rake, were obtained in this test. The main purpose of these last two apecial tests, was to check on a phenomenon present in the original test, with regard to diameter size changes.

LIMITATIONS

One disadvantage of using the regular gear driven engine lathe, is that one is limited in one's selection of individual speeds. This is detrimental when one must make more than one pass along the bar with the same tool. The reduction of the diameter changes the surface speed and changes the cutting conditions. This could be avoided by using a machine with an infinite number of speeds obtained by varying the electrical input to the machine, or some similar procedure.

In the measuring instruments, it is usually best to use ones that provide a permanent record of the reading. This is especially true with surface finish which may vary in a short distance of the cut. When using the profilometer with the hand trace, it was necessary to average the needle deflections over the length of cut while still attempting to make a good hand trace. One thing that would help to alleviate some of this problem is the use of a mechanical trace instead of the hand trace. This will tend to give more consistent readings, by eliminating the human variance. Of course a recording device attached to the profilometer would help the problem immensely.

In the use of the tool inserts, an additional variable can be eliminated, by only using the edges on the one side of the tool. The heat from the one side may adversely affect the opposite edge. The edge on the other side may also be weakened by the near or complete catastrophic failure of the tool edge being used.

RESULTS

Data

The raw data obtained from this study is presented in its entirety in Appendix A of this report. Therefore, any reference made to the data will be in reference to that section.

Analysis

In presenting the analysis of the data obtained in this study, a breakdown into three specific areas will be used. These three areas are as follows (1) "critical point," (2) size change of the diameter, and (3) plastic deformation.

The first area of discussion will be for the "critical point". The land wear of the tools was plotted against time on log-log paper, to check on the work of Takeyama, et. al.[6] A sample of these plots is seen in Appendix C (pp. 47-51). An attempt was made to draw the plot as two straight lines, the point of intersection being the "critical point." The results of these plots show that this "critical point" as seen here varies over a range from 0.016 in. to 0.033 in. land wear.

In addition to these curves, the land wear was also plotted against surface finish and tool forces. A sample of these plots is seen in Appendix C (pp. 52-53). These results did not show any obvious reasons for the occurrance of the "critical point" on the land wear vs. time curves. The only thing obvious from these plots was that the surface finish grew worse and the forces increased as the flank wear increased.

The next area is the one dealing with the change in size of the diameter. In analyzing the change in diameter size, as recorded in Appendix A, we will start with the results obtained by analysis of tools #1 - 9. This analysis is contained in Appendix B (p. 43). From the analysis presented there, it is seen that a breakdown of the starting diameters compared with the final diameters, makes obvious the fact that in only a small number of the cases was the starting diameter smaller than the final diameter. As cited earlier in the paper, an increase in diameter size may be a criterion for determining tool wear. This fact should be kept in mind at this point.

The analysis then proceeds on the hypothesis that the probability of obtaining a smaller final diameter is equal to the probability of a larger final diameter. Thus using this hypothesis and the actual results obtained even splitting the ties (equals) , we apply a t-test to the distribution and find that t is very large. Therefore, we can say that our hypothesis is not true and that our results were obtained from a different distribution than the assumed one.

Since these original tests had all been performed on negative rake tools, these first results lead us to a test using both positive and negative rake tools. The results of these tests are tabulated in Appendix B (p. 44). In analyzing these results, the results of the positive tool were checked against the distribution of the original data to see if they were from different populations. As seen in the analysis, a t-test was applied here, with the results showing that $t = 2.2$ for 24 degrees of freedom was significant at the five per cent level. This means that the tests did not show the results came from different populations.

Further analysis was done in the comparison of the results of the positive and negative rake tool test. The next analysis (p. 45) was performed to see if the differences in diameter sizes, for both the positive and negative rake tools, came from different populations. To do this, an F-test was performed on the data, which is a ratio of variances from the two sets of data. The results of the F-test, $F = 1.5$ for 24 degrees of freedom, showed that $F = 1.5$ is significant at the 20 per cent level. Therefore the diameter differences were not shown to be from different populations.

Two other analyses were performed on the original data (Tools #1-9) in this area. Reference is made here to the histograms in Appendix B (p. 15). Figures 1 and 2 here show histograms of the frequency as a percentage of the total number of observations, with which the phenomenon of the starting diameter being greater than the final diameter occurs in the different ranges of land wear and feeds. Figure 1 shows no definite pattern, however it can be seen from figure 2 that the phenomenon being tested occurred more frequently in the lower feed ranges than it did at the higher feeds.

In order to check on the causes of the changes in diameter size, tests were run to check on the movement of the tool post and

Histograms (Tools #1-9)

Fig. 1
Land Wear Frequency of
Starting Dia. Final Dia.

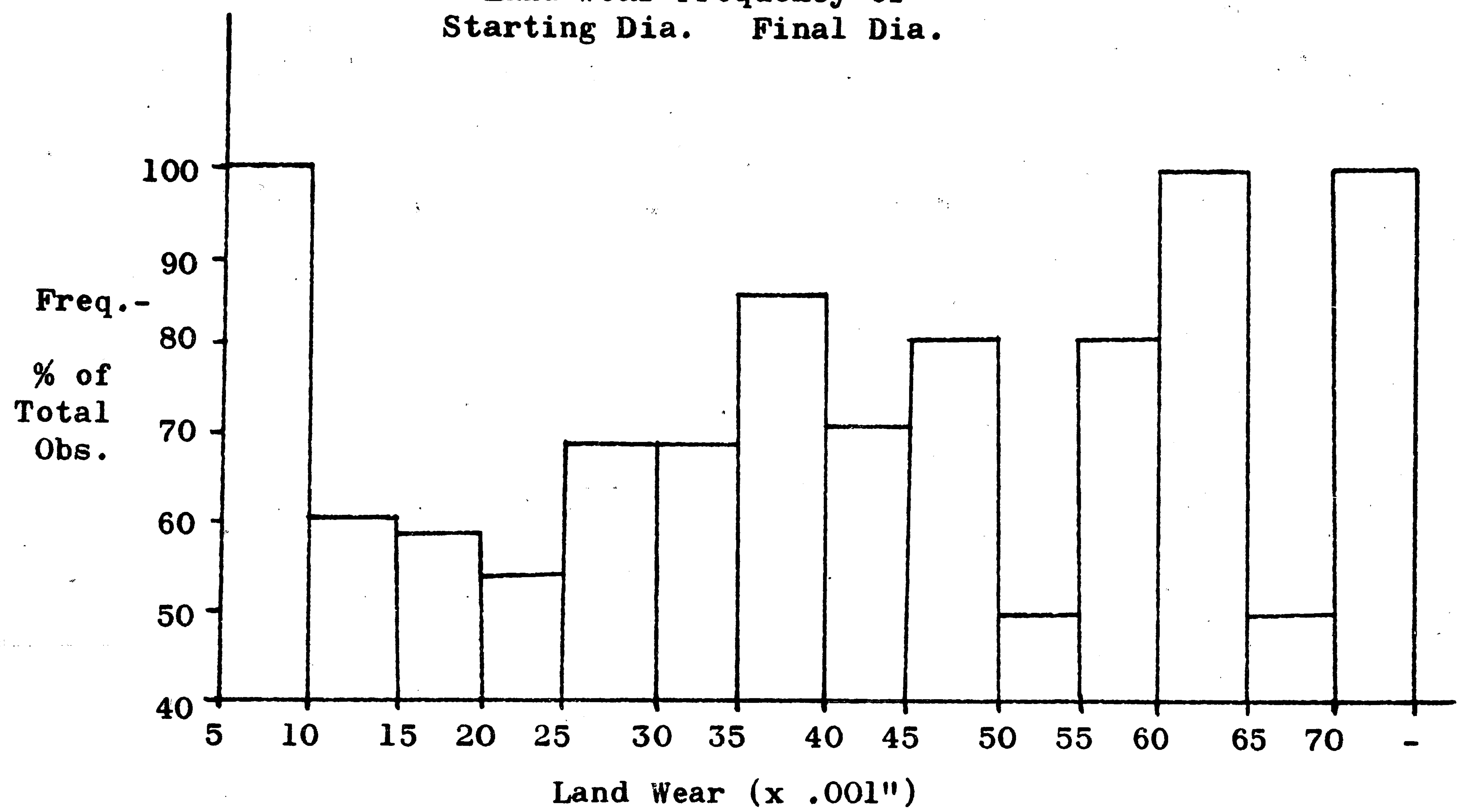
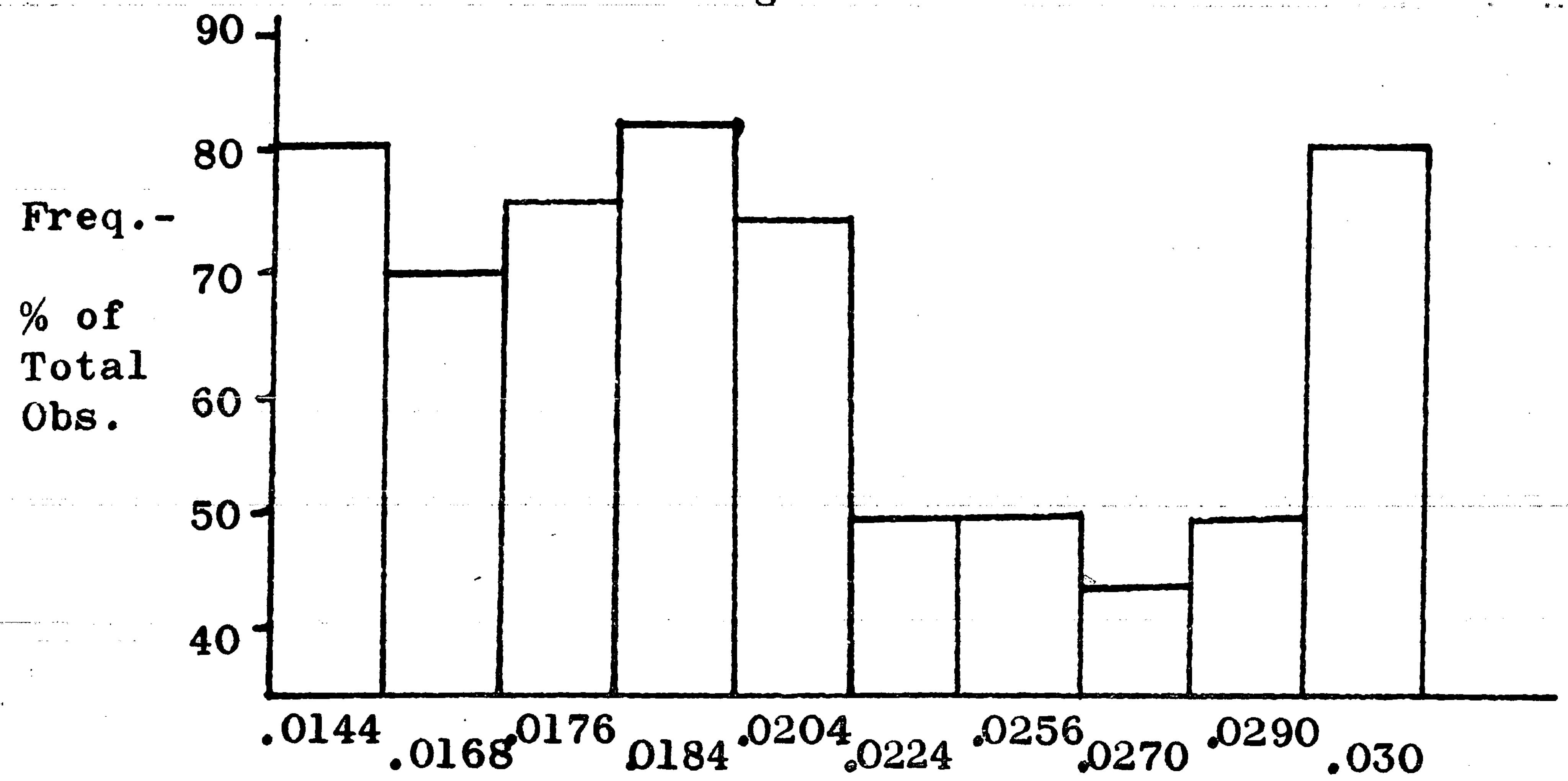


Fig. 2
Feed Frequency of
Starting Dia. Final Dia.



cross slide. The results of this test may be seen in Appendix A (pp. 38-40) under the column of dial indicator readings. The plus sign here signifies that the movement was away from the work, the minus sign means that the tool moved into the work, and the blank means that there was no significant movement (less than 0.00025). The results on tool number ten (p. 38) show that the tool moved both ways, which seemed to be caused by the play in the cross slide (negative movement) and radial pressure against the tool (positive movement).

The results for tools #11-14 were slightly different in that most of the movement was toward the work. The reason submitted here for the lack of movement away from the work, is the fact that the tools were slightly different and that the cutting conditions were less severe, therefore producing a small radial force against the tool. In any case, the movement of the tool that was measured was not sufficient to account for the difference in diameter size.

This leads to the final area of discussion, that being plastic deformation. When looking at the flank wear of a tool on the optical comparator, it was noticed that there was a raised portion of tool material present on the flank, often resembling a bubble. This can be seen by the illustration in figure 3.

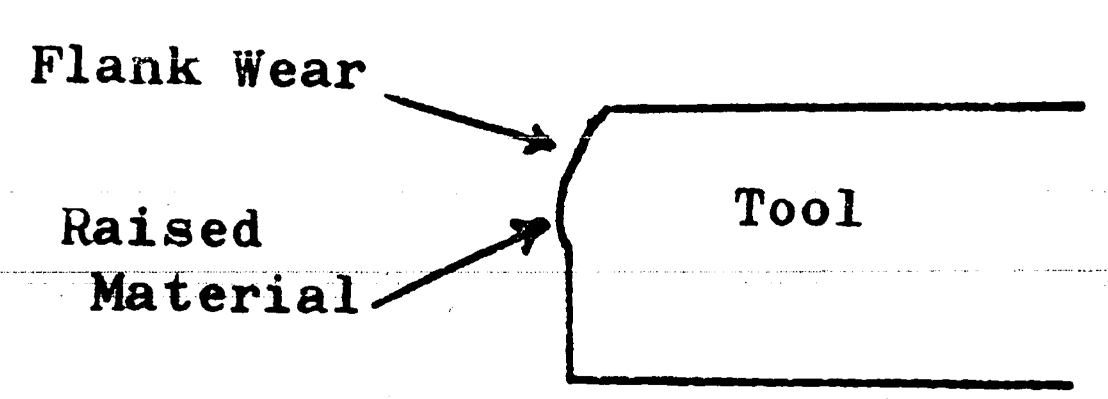


Fig. 3 - Side View of Worn Tool

For clarity, further reference to this raised portion will be made by referring to the plastic deformation, even though this may not be the exact cause.

The results showing an amount and location of this plastic deformation for all the tools used in this study are shown in Appendix A (p. 41). These measurements were made at the end of the tool wear, thus they show deformation at usually high amounts of tool wear.

The sample calculation shown in Appendix D (p. 55) shows that in some cases this plastic deformation extends outward beyond the point of the original cutting edge. Also, even though it is somewhat below the center line of the work, the calculations show that in some cases it could be making contact with the work material. The example shown for one particular tool shows that the plastic deformation extended a sufficient distance beyond the original edge, to be acting as its own cutting edge, and thus reducing the diameter.

CONCLUSIONS

1. The work involving the "critical point," agrees with the findings of Takeyama, et. al., to some degree. However, it should be stated that there is not entire agreement, because of the fact that the data shows there may be a better fit to the points than the two straight lines.

Another point of disagreement is the range into which this "critical point" falls. For the Takeyama, et. al., test conditions and tools, the "critical point" varied from 0.0158 in. to 0.0177 in. These test results showed that the "critical point" varied from 0.016 in. to 0.033 in., which seems to show that this "critical point" is going to be different for different materials and cutting conditions.

2. The location of the "critical point" on the land wear curve could not be correlated with either surface finish or tool forces, as measured in this experiment.

3. For the negative rake tools #1-9 used in this test, it can be concluded that when there is a change in diameter size it will usually be a reduction. This was done on cuts varying in length from 3 to 7 inches long. This is in contradiction to the common theory that the diameter size should increase as the tool wears.

4. From the limited tests run on the positive rake tools (#12, 14), there was no evidence to show that they were from a different population than the negative rake tools. Therefore, this phenomenon may also exist in the positive rake tools.

5. No basis could be established for stating that the diameter differences would be of a different magnitude for the positive rake tools, as opposed to the negative rake tools.

6. A significant difference was noted in the occurrence of the reduced diameters over the feed range tested. It was shown that the frequency of occurrence of the reduced diameter was greater at the lower feeds than it was at the higher feeds tested.

7. The flank of the tools,definitely displayed a plastic deformation of some kind. And, the thought is here, that the plastic deformation probably took place along the slip planes of the binding material rather than across the carbide, since carbide has a value for Young's Modulus of about 94,000,000 psi.

8. From the tests performed to find a cause for the reduction in diameter size, it was concluded that this reduction was being caused, at least in part, by the plastically deformed portion on the tool flank. It is thought that the plastically deformed material is acting as a secondary cutting edge, and thus reducing the diameter size as the cut progresses and the deformation increases.

RECOMMENDATIONS FOR FURTHER STUDY

1. One area that would lend itself to much further study is the area dealing with the "critical point." Several suggestions can be offered here for ways of approaching this area. The data from this study could be used to, first of all, check on the fit of the two straight lines on the log-log plots, to make sure that this is the best fit for the data. There seems to be some doubt from looking at the land wear vs. time plots that the two stage plot is the best fit. Then, if it is found to be the best fit, the problem of fitting the best two straight lines to the data is the next problem. This can be solved by least squares technique, finding the fit with the least error.

2. After locating and justifying the presence of the "critical point," one should then proceed to do a thorough statistical analysis of the data presented here, to determine if any of the factors measured; surface finish, forces, and diameter change, can be directly related to the occurrence of the "critical point."

3. From the data available here, there seems to be much evidence that the location of the "critical point" is going to vary under different conditions. An attempt should then be made to tie down the cause or causes of the variation in the "critical point."

4. The reduction of diameter size which was observed in this study should be further observed in the area of positive rake tools, for different materials, and also for different cutting conditions. This should be done so as to find when this phenomenon becomes important in the process of holding sizes. This phenomenon would also lend itself as an ideal practical measure in determining tool life of tools, and work should be done to try and correlate this size change to the "critical point" previously discussed.

5. In further studying the reduction in diameter size, a study should be made to determine what portion is caused by play in the cross slide, plastic deformation, and the opposing phenomenon of the tool wearing and tending to increase diameter size. A study should be made to separate these causes and determine their degree of importance.

6. Another major area that was observed is the deformation on the flank of the carbide tools. Many questions remain to be answered as to the cause of this deformation. For instance, is it due in part to the crater wear, does the deformation take place along the slip planes of the binding material, and what is the strength of this plastically deformed portion of the tool? When a cause is found for this deformation, then further study could be made on the different grades of tools that are specified for different cutting conditions, to evaluate the importance of this deformation.

APPENDIX A

Raw Data

Tool #1 (1, 2, 3, 4 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Tool Forces (lbs) H	Tool Forces (lbs) V	Surface Finish (m-in.)	Initial Dia.	Dia. of Cut Start	Dia. of Cut Finish	SFPM
50	270	.0184	.0166	310	625	240	6.919	6.725		497
25			.0176	340	625	-		6.729		
25			.0177	350	625	-		6.729		
25			.0198	370	625	275		6.729		
25			.0203	390	625	-		6.729		
25			.0198	420	650	-		6.725		
25			.0264	430	650	300		6.730		
25			.0281	440	650	-		6.730		
25			.0306	450	650	-		6.731		
25			.0307	480	650	-		6.731		
25			.0342	475	650	-		6.732		
25			.0364	500	675	325		6.733		
50			.0400	450	675	350		6.731		
50			.0421	375	650	360		6.728		
50			.0401	350	625	360		6.728		
50			.0475	325	625	360		6.728		
50			.0478	325	625	375		6.728		
250			.0571	325	625	400		6.723		
25	270	.0224	.0166	380	700	350	6.725	6.529	6.530	483
25			.0198	440	725	350		.532	.532	
20			.0251	550	750	400		.534	.535	
20			.0316	625	775	400		.538	.539	
20			.0390	725	800	450		.543	.544	
20			.0512	750	800	450		.547	.547	
15	270	.027	.0198	450	800	450	6.730	6.531	6.532	
15			.0255	625	850	500		.531	.532	
15			.0360	775	875	500		.539	.543	
15			.0544	950	900	550		.550	.552	
10	270	.030	.0225	500	850	600	6.730	6.537	6.539	
10			.0291	625	875	-		.542	.544	
10			.0360	750	925	700		.548	.550	
10			.0498	900	925	-		.557	.560	
10			.0658	950	925	800		6.575	.575	

Tool #2 (1, 2 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
30	270	.0184	.0135	6.535	6.535	6.730	250	260	575	483
20			.0146	-	-		250	270	575	
25			.0165	.536	.536		250	300	575	
25			.0194	.536	.536		250	320	575	
25			.0211	.537	.536		250	340	600	
25			.0221	.537	.536		275	360	600	
25			.0235	.538	.537		275	370	625	
25			.0285	-	-		275	380	625	
25			.0275	-	-		300	400	625	
25			.0281	.539	.538		300	400	650	
25			.0326	.539	.538		300	430	650	
25			.0334	.539	.538		325	430	650	
25			.0365	.540	.538		350	425	650	
50			.0392	.539	.538		350	375	650	
50			.0452	.539	.538		350	350	625	
50			.0454	6.535	6.534		350	350	625	
50	270	.0168	.0113	6.331	6.331	6.538	250	250	550	470
50			.0133	-	-		250	290	575	
50			.0150	-	-		250	320	625	
50			.0173	-	-		250	340	625	
50			.0191	.333	.332		250	350	625	
50			.0202	-	-		250	350	625	
50			-	-	-		250	370	650	
50			.0210	-	-		250	350	650	
50			.0221	-	-		250	350	650	
50			.0239	.333	.332		250	350	650	
50			.0255	-	-		250	350	650	
50			.0268	-	-		250	350	650	
50			.0273	-	-		300	375	650	
50			.0293	-	-		350	375	675	
50			.0315	.329	.328		350	375	675	
50			.0335	-	-		350	375	675	
50			.0361	.331	.328		400	375	675	

Tool #2 (3, 4 edge)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
50	270	.0176	.0216	6.135	6.134	6.330	220	320	575	454
50			.0259	.135	.134		220	370	600	
50			.0288	.135	.134		230	400	625	
50			.0319				230	430	650	
50			.0368	.136	.136		240	475	650	
50			.0391				250	500	675	
50			.0424	.138	.137		250	525	675	
50			.0446	.137	.135		270	475	675	
50			.0577	.138	.134		270	475	675	
100			.0620	.139	.134		270	425	675	
100			.0624	.140	.133		270	400	675	
50	270	.0184	.0146	5.935	5.934	6.130	280	270	600	440
50			.0145	.936	.934		280	310	600	
50			.0176	.935	.934		280	330	625	
50			.0189	.935	.934		280	360	650	
50			.0212	.936	.934		280	370	650	
50			.0225	.935	.933		280	380	675	
50			.0248	.935	.932		280	360	650	
50			.0255	.933	.931		280	360	650	
50			.0261	.934	.932		280	360	650	
50			.0285	.934	.930		280	350	650	
50			.0299	.933	.932		280	350	675	
50			.0312	.932	.930		280	350	675	
50			.0328	.931	.929		280	350	675	
150			.0357	.933	.930		300	375	675	

Tool #3 (1, 2 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
5	270	.0204	.0112	5.739	5.737	5.934	350	-	-	425
45			.0162	.740	.739		350	290	625	
50			.0187	.740	.739		350	340	650	
50			.0202	.740	.740		350	360	650	
50			.0218	.740	.739		350	380	675	
50			.0246	.739	.738		350	390	675	
50			.0266	.739	.739		350	390	675	
50			.0270	.739	.738		350	390	675	
50			.0275	.739	.737		350	380	700	
50			.0292	.740	.741		350	380	700	
50			.0298				400	375	700	
50			.0305	.740	.740		400	375	725	
50			.0318	.740	.738		400	400	750	
50			.0342	.740	.739		400	425	750	
50			.0388	.740	.738		400	475	775	
2	270	.0224	.0060	-	-	5.740	-	290	650	412
48			.0150	5.545	5.546		550	320	700	
50			.0174	.547	.546		600	360	725	
50			.0191	.548	.548		600	390	725	
50			.0210	.549	.549		650	410	750	
50			.0223	.549	.549		600	420	750	
50			.0239	.550	.549		700	430	750	
50			.0257	.550	.550		750	440	775	
50			.0267	.551	.551		800	450	775	
50			.0374	.550	.550		850	475	800	
50			.0380	.549	.547		850	450	800	
50			.0412	.552	.550		850	450	800	
50			.0477	.549	.549		850	425	775	

Tool #3 (3, 4 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
3	270	.0256	.0073	-	-	5.550	-	370	750	398
47			.0173	5.352	5.354		600	430	800	
50			.0224	.357	.357		650	500	825	
50			.0264	.359	.359		700	-	-	
50			.0288	.362	.362		800	600	850	
50			.0340	.365	.363		800	650	875	
50			.0377	.366	.365		800	675	900	
50			.0420	.367	.366		800	700	900	
50			.0453	.368	.364		800	725	925	
50			.0505	.367	.367		800	725	925	
50			.0549	.369	.370		850	750	925	
50			.0572	.367	.363		850	750	900	
3	270	.027	.0092	-	-	5.360	-	130	775	385
47			.0171	5.154	5.154		450	380	800	
50			.0206	.156	.156		450	430	850	
50			.0229	.157	.157		500	460	875	
50			.0242	.158	.158		500	500	900	
50			.0259	.158	.157		500	500	900	
50			.0282	.157	.157		500	525	925	
50			.0299	.157	.157		500	550	950	
50			.0316	.157	.157		550	575	950	
50			.0346	.157	.157		550	600	975	
50			.0354	.157	.156		550	600	975	
50			.0381	.155	.154		600	650	1000	

Tool #4 (1, 2 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
3	270	.029	.0091	-	-	5.157	-	350	800	370
50			.0181	4.959	4.960		700	400	850	
47			.0221	.963	.963		700	450	875	
50			.0243	.965	.965		700	475	875	
50			.0273	.966	.965		750	525	900	
50			.0290	.967	.967		750	550	900	
50			.0320	.967	.967		800	575	925	
50			.0341	.968	.967		850	600	925	
50			.0355	.967	.966		900	625	950	
50			.0378	.966	.965		950	650	975	
50			.0405	.966	.965		950	700	975	
3	394	.0144	.0078	-	-	4.965	-	210	450	511
47			.0129	4.762	4.761		160	230	450	
50			.0149	.762	.761		160	250	475	
50			.0161	.762	.761		160	260	500	
100			.0183	.762	.760		170	280	500	
100			.0225	.761	.760		170	300	525	
100			.0262	.760	.758		170	300	525	
50			.0288	.762	.758		150	300	525	
50			.0308	.760	.757		150	300	525	
50			.0341	.761	.758		140	300	525	
50			.0379	.762	.759		150	300	525	
50			.0361	.760	.758		140	300	525	

Tool #4 (3, 4 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
3	394	.0168	.0152	-	-	4.760	-	250	500	490
50			.0197	4.562	4.562		190	270	525	
47			.0256	.564	.563		200	310	550	
50			.0288	.565	.564		200	340	575	
50			.0335	.565	.564		200	350	575	
50			.0373	.565	.564		200	330	575	
50			.0389	.565	.565		200	320	575	
50			.0468	.565	.565		210	320	575	
50			.0400	.565	.563		210	320	575	
100			.0512	.566	.561		220	300	575	
97			.0567	.561	.558		250	325	575	
3	394	.0176	.0081	-	-	4.565	-	240	525	470
50			.0156	4.367	4.368		220	270	550	
47			.0180	.367	.366		230	310	575	
50			.0200	.367	.366		220	330	600	
50			.0225	.367	.366		230	330	600	
50			.0245	.365	.365		230	330	625	
50			.0259	.366	.365		230	340	625	
50			.0286	.367	.367		240	350	625	
50			.0300	.365	.364		250	350	625	
50			.0310	.365	.363		250	350	625	
50			.0340	.365	.365		260	360	650	
50			.0348	.365	.363		280	350	625	

Tool #5 (1, 2 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
3	394	.0184	.0060	-	-	-	-	220	550	450
47			.0114	4.169	4.169	4.365	280	250	550	
50			.0130	.169	.168		280	280	575	
50			.0142	.170	.170		280	300	600	
50			.0165	.170	.169		280	300	600	
50			.0173	.170	.169		270	300	600	
50			.0178	.169	.168		290	310	600	
50			.0185	.170	.169		280	310	625	
50			.0191	.170	.168		300	320	625	
50			.0203	.169	.168		290	320	625	
50			.0206	.168	.166		290	330	625	
50			.0218	.169	.167		300	320	625	
100	394	.0184	.0245	3.967	3.967	4.169	280	350	650	429
100			.0255	.970	.970		290	360	650	
100			.0275	.970	.970		300	375	675	
100			.0289	.969	.969		290	375	675	
150			.0312	.972	.967		290	375	675	
3	394	.0224	.0074	-	-	3.970	-	260	650	409
97			.0157	3.770	3.770		400	310	675	
100			.0193	.772	.773		400	350	700	
100			.0217	.770	.768		375	370	750	
100			.0262	.773	.770		350	420	800	
50			.0272	.769	.767		350	400	750	
100	394	.0224	.0242	3.572	3.572	3.770	400	400	750	388
100			.0255	.574	.575		400	400	750	
100			.0278	.576	.576		400	400	775	
100			.0292	.576	.572		450	425	775	
50			.0300	.573	.570		450	425	775	
100	394	.0224	.0310	3.376	3.376	3.576	450	425	775	368
100			.0318	.378	.378		500	425	800	
100			.0344	.380	.377		600	425	800	
100			.0340	.379	.377		650	425	800	
50			.0345	.378	.380		-	425	800	

Tool #5 (3, 4 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
3	394	.0224	.0060	-	-	3.377	-	280	650	348
97		.0224	.0112	3.181	3.183		400	280	650	
100		.0256	.0150	.181	.183		500	350	750	
100			.0177	.185	.182		600	370	775	
100			.0197	.181	.178		600	400	800	
100	394	.0256	.0202	2.987	2.989	3.181	600	400	800	327
100			.0214	.990	.990		550	410	800	
100			.0215	.992	.990		550	430	825	
100			.0226	.990	.985		550	475	825	
100	394	.0256	.0237	2.789	2.792	2.990	600	500	850	308
100			.0240	.796	.798		600	500	825	
100			.0242	.800	.796		650	500	850	
100			.0258	.798	.791		700	500	850	
4	270	.0144	.0055	-	-	6.930	-	200	450	497
46			.0098	6.725	6.724		110	220	475	
50			.0114	.730	.730		120	240	475	
100			.0137	.729	.729		110	260	500	
100			.0169	.732	.731		100	270	500	
100			.0185	.733	.733		100	290	525	
125			.0214	.735	.735		120	300	525	
75			.0234	.737	.735		150	300	525	
100			.0275	.738	.736		140	310	550	
100			.0296	.735	.734		150	310	550	
100			.0341	.735	.734		120	320	550	
100			.0391	.735	.733		120	320	550	
20			fail					320	725	

Tool #1 (5, 6 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
3	270	.0168	.0094	-	-	6.735	-	220	525	483
47			.0133	6.526	6.526		200	250	550	
50			.0164	6.527	6.526		200	300	575	
100			.0221	.527	.526		200	340	600	
100			.0282	.527	.527		210	400	625	
100			.0333	.528	.528		230	450	650	
100			.0390	.529	.526		300	500	650	
100			.0424	.528	.525		300	500	650	
100			.0718	.531	.528		400	625	700	
4	270	.0176	.0066	-	-	6.527	-	220	525	470
46			.0128	6.329	6.329		260	250	550	
50			.0153	.330	.329		260	290	575	
100			.0194	.330	.328		260	320	600	
100			.0245	.327	.327		280	400	625	
100			.0297	.329	.328		300	440	675	
100			.0330	.328	.325		300	475	725	
100			.0488	.327	.326		350	625	750	

Tool #6 (1, 2 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
4	270	.0176	.0065	-	-	6.329	-	220	525	454
46			.0111	6.133	6.132		290	230	525	
50			.0131	.134	.133		290	260	550	
100			.0168	.134	.133		300	300	575	
100			.0194	.135	.134		300	310	600	
100			.0225	.134	.134		290	350	625	
100			.0253	.136	.134		300	350	625	
100			.0279	.135	.134		300	400	650	
100			.0295	.134	.135		300	400	675	
1000			.0320	.135	.132		300	425	675	
50			.0341	.134	.132		300	425	675	
4	270	.0184	.0081	-	-	6.134	-	230	550	440
50			.0109	5.931	5.930		260	240	550	
46			.0127	.932	.931		270	270	575	
100			.0161	.932	.930		280	300	600	
100			.0187	.932	.931		260	320	625	
100			.0213	.931	.931		260	330	650	
100			.0233	.932	.930		270	380	675	
100			.0267	.931	.928		300	380	700	
100			.0280	.930	.927		300	375	700	
50			.0308	.930	.927		350	375	700	
60			.0370	.930	.927		400	400	700	

Tool #6 (3, 4 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
4	270	.0204	.0061	-	-	5.931	-	250	600	425
46			.0119	5.733	5.732		350	270	600	
50			.0140	.733	.732		350	320	625	
50			.0159	.734	.733		350	340	650	
100			.0204	.734	.733		350	380	675	
100			.0231	.735	.735		350	400	700	
100			.0267	.737	.735		350	425	725	
100			.0287	.737	.734		400	425	725	
50			.0332	.735	.734		400	375	725	
50			.0313	.733	.733		400	400	700	
83			.0352	.738	.733		400	400	725	
4	270	.0224	.0105	-	-	5.733	-	280	650	412
46			.0166	5.541	5.540		400	310	650	
50			.0198	.542	.542		400	360	675	
50			.0216	.544	.543		400	390	700	
50			.0254	.545	.545		400	410	725	
100			.0308	.546	.545		400	470	750	
100			.0415	.546	.545		450	525	775	
100			.0417	.546	.546		450	500	775	
50			.0443	.545	.545		450	475	775	
50			.0562	.543	.544		500	450	775	
55			.0518	.544	.545		550	425	700	

Tool #7 (1, 2, 3, 4 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
4	270	.0256	.0088	-	-	5.545	-	290	700	398
46			.0163	5.346	5.346		350	330	725	
50			.0196	.347	.347		350	390	750	
100			.0279	.345	.345		350	440	800	
50			.0300	.350	.350		350	500	825	
50			.0337	.352	.351		400	525	850	
50			.0433	.351	.351		400	575	850	
50			.0381	.352	.350		400	625	875	
50			.0524	.352	.351		400	700	925	
50			.0671	.351	.350		400	725	950	
553	270	.0270	.0506	5.149	5.155	5.350	400	300	750	385
							650	650	975	
4	270	.0290	.0066	-	-	5.152	-	320	800	370
46			.0124	4.954	4.954		650	340	800	
50			.0174	.955	.955		650	380	825	
50			.0191	.957	.956		650	410	850	
50			.0221	.956	.956		650	440	875	
50			.0240	.958	.958		600	475	900	
50			.0261	.959	.957		650	500	900	
50			.0285	.958	.958		700	525	925	
50			.0312	.958	.957		750	550	925	
50			.0340	.958	.958		800	600	950	
60			.0361	.958	.957		800	625	975	
3	394	.0144	.0070	-	-	4.957	-	190	450	511
47			.0101	4.751	4.751		140	200	450	
50			.0121	.753	.752		140	230	475	
50			.0137	.753	.752		140	250	500	
100			.0160	.753	.752		150	270	500	
100			.0189	.752	.752		170	290	525	
100			.0221	.751	.751		180	300	550	
100			.0241	.752	.751		180	310	550	
50			.0252	.757	.754		220	300	550	
50			.0266	.754	.753		220	300	550	
60			.0312	.754	.752		230	300	550	

Tool #8 (1, 2, 3, 4 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
3	394	.0168	.0070	-	-	4.753	-	220	500	490
47			.0116	4.554	4.553		200	230	525	
50			.0135	.555	.554		200	270	550	
50			.0156	.555	.555		210	290	575	
50			.0187	.554	.553		200	310	575	
100			.0222	.554	.554		210	330	600	
100			.0250	.557	.555		210	330	600	
50			.0275	.557	.555		230	330	600	
50			.0308	.555	.554		230	340	600	
50			.0315	.555	.555		220	340	600	
58			.0330	.555	.553		230	350	600	
588	394	.0176	.0328	4.356	4.352	4.555	200	210	525	470
							300	400	700	
3	394	.0184	.0073	-	-	4.354	-	220	525	450
97			.0141	4.159	4.158		270	260	575	
100			.0178	.160	.160		260	320	600	
100			.0226	.162	.161		280	350	625	
100			.0250	.163	.160		270	370	650	
100			.0295	.162	.160		270	380 475	675	
55			.0310	.160	.159		290	450	700	
575	394	.0184	.0284	3.964	3.962	4.160	280	220	525	429
							280	390	675	

Tool #9 (1, 2 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	SFPM
3	394	.0224	.0052	-	-	3.963	-	240	625	409
97			.0128	3.771	3.771		350	280	650	
100			.0172	.773	.773		350	330	675	
100			.0201	.772	.771		400	360	700	
155			.0248	.771	.772		400	390	725	
95	394	.0224	.0255	3.575	3.575	3.772	450	380	750	388
100			.0261	.579	.578		450	390	750	
100			.0281	.579	.577		450	425	775	
150			.0321	.579	.579		500	425	800	
100	394	.0224	.0321	3.385	3.385	3.578	600	450	800	368
100			.0329	3.387	3.390		650	475	800	
100			.0350	.390	.389		800	475	800	
150			.0411	.390	.385		850	525	850	
3	394	.0256	.0055	-	-	3.390	-	370	725	348
97			.0202	3.185	3.186		400	390	750	
100			.0260	.189	.189		450	450	800	
100			.0317	.191	.187		500	525	825	
100			.0385	.189	.185		500	575	850	
100	394	.0256	.0390	2.989	2.991	3.189	500	500	825	327
100			.0410	.995	.996		500	500	825	
100			.0438	.999	.996		500	500	825	
100			.0471	.996	.991		500	500	850	
100	394	.0256	.0474	2.792	2.796	2.995	500	500	850	308
200			.0513	.798	.795		500	500	850	
100			.0539	.797	.792		500	500	875	

Tool #10 (1, 2, 3, 4 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	Tool Forces (lbs) H	Tool Forces (lbs) V	Dial Indicator (.001 in.)
100	270	.0144	.0116	6.619	6.619	6.835	250	250	475	-
200			.0184	.621	.621		270	300	525	-
200			.0222	.620	.621		290	330	550	+¼
200			.0276	.622	.621		300	330	550	+½,-1
200			.0353	.623	.618		350	340	550	-1½
150			.0464	.626	.621		400	330	550	-¾
150	270	.0168	.0158	6.415	6.415	6.621	250	290	575	+½
150			.0211	.420	.419		250	340	600	+¼
150			.0243	.421	.419		260	350	600	+¼,0
150			.0295	.419	.417		300	350	600	-¼
150			.0334	.418	.416		350	350	600	0,-½
160			.0416	.419	.416		650	350	625	-1,+¼
150	270	.0176	.0160	6.215	6.215	6.419	250	280	550	+¼
200			.0224	.219	.219		280	340	600	+¼
150			.0262	.217	.217		300	350	600	+½
150			.0304	.222	.219		350	350	600	+¼,-1
210			.0434	.222	.219		450	350	600	-1,-½
150	270	.0184	.0198	6.014	6.014	6.219	250	320	575	+½
150			.0247	.014	.014		270	360	625	+½
150			.0314	.024	.024		270	360	600	+½
150			.0376	.025	.023		300	360	600	+¼
230			.0536	.025	.020		450	350	625	+½,0

Tool #11 (1, 2, 3 edges)

Tool #12* (1, 2, 3 edges)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	SFPM	Dial Indicator (.001 in.)
100	270	.0224	.0230	5.521	5.521	5.728	500	405	+½
100			.0338	.525	.525		550		-
100			.0499	.530	.536		700		-
* 100	270	.0224	.0291	5.527	5.530	5.728	450	405	-¼
100			.0370	.533	.536		500		-
100			.0475	.538	.540		500		-
75			.0497	.540	.535		500		-
* 100	270	.0176	.0169	5.322	5.323	5.533	400	392	-
150			.0228	.326	.325		400		-
150			.0294	.327	.327		400		-
150			.0352	.330	.330		400		-
150			.0402	.332	.330		400		-
155			.0443	.332	.331		450		-
100	270	.0176	.0124	5.119	5.117	5.325	450	377	-¼
150			.0170	.114	.110		450		-
150			.0209	.116	.113		RGH		-
150			.0244	.112	.109		550		-¼
150			.0280	.111	.108		550		-¼
155			.0329	.108	.106		550		-¼
100	270	.0204	.0124	4.918	4.916	5.113	500	362	-
150			.0176	.923	.921		450		-
150			.0215	.921	.918		500		-¼
150			.0242	.918	.916		500		-
100			.0258	.915	.912		550		-
90			.0278	.912	.911		550		-¼
* 100	270	.0204	.0190	4.717	4.718	4.915	400	348	-¼
150			.0253	.721	.720		400		-¼
150			.0287	.722	.723		450		-½
150			.0326	.725	.722		450		-
100			.0369	.723	.723		450		-
90			.0410	.723	.722		450		-

Tool #11 (4 edge)

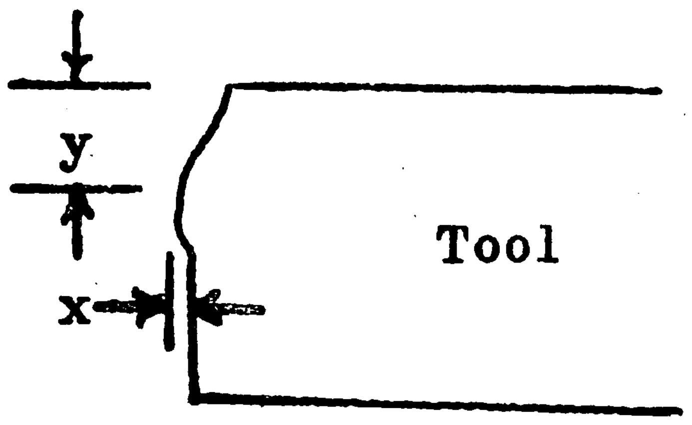
Tool #12* (4 edge)

Tool #13 (1 edge)

Tool #14* (1 edge)

Time Interval (minx100)	Speed (rpm)	Feed (in/rev)	Land Wear	Dia. of Cut Start	Dia. of Cut Finish	Initial Dia.	Surface Finish (m-in.)	SFPM	Dial Indicator (.001 in.)
* 100	394	.0144	.0152	4.515	4.517	4.722	220	489	-¼
150			.0235	.519	.518		240		-
150			.0293	.521	.518		350		-¼
150			.0707	.523	.522		350		+¼
100	394	.0144	.0118	4.312	4.311	4.519	150	468	-
150			.0156	.313	.311		100		-
150			.0242	.314	.314		80		-¼
150			.0327	.321	.318		350		-
165			.0349	.317	.314		350		-¼
100	394	.0168	.0147	4.110	4.108	4.314	400	447	-
150			.0197	.120	.118		400		-¼
150			.0268	.112	.111		400		-¼
100			.0311	.108	.108		450		-
110			.0351	.110	.109		500		-¼,0
* 100	394	.0168	.0185	3.908	3.907	4.110	400	426	-¼
150			.0266	.909	.908		400		-¼
150			.0330	.910	.910		240		-
100			.0342	.915	.912		250		-
110			.0367	.913	.911		300		-¼

Tool No.	Edge No. 1 x	1 y	2 x	2 y	3 x	3 y	4 x	4 y
1	-	-	-	-	.0013	.0645	.0007	.0546
2	.0010	.0232	.0011	.0237	.0012	.0385	.0009	.0298
3	.0026	.0247	.0013	.0357	.0009	.0417	.0026	.0204
4	.0014	.0477	.0006	.0185	.0007	.0280	.0008	.0276
5	.0037	.0274	.0047	.0306	.0018	.0203	.0022	.0502
6	.0016	.0285	.0016	.0253	.0019	.0283	.0021	.0312
7	.0028	.0337	.0029	.0332	.0024	.0263	.0010	.0274
8	.0022	.0251	.0014	.0255	.0022	.0234	.0017	.0208
9	.0032	.0269	.0030	.0256	-	-	-	-
10	.0006	.0327	.0023	.0257	.0009	.0348	.0018	.0267
11	.0060	.0332	.0040	.0280	.0031	.0264	.0030	.0269
12	.0047	.0458	.0029	.0454	.0033	.0389	.0040	.0418
13	.0047	.0325						
14	.0022	.0362						
1A	.0030	.0350	.0013	.0281				



APPENDIX B

Analysis of Diameter Size Change

Analysis of Diameter Size Changes

Tools 1-9
Starting Diameter - Final Diameter

		freq.
Greater than	-	215
Equal	-	90
Less than	-	24

$$P_r\left[d_s > d_f\right] = p \qquad H_0:\ p = \frac{1}{2} = q$$

$$P_r\left[d_s < d_f\right] = q$$

It is conservative to split ties:

greater than	-	215 + 45	=	260
less than	-	24 + 45	=	69
		Total		329

$$E = n\,p = \frac{1}{2}(329) = 164.5$$

t-test

$$t = \frac{\bar{x} - E}{\sqrt{n\,p\,q}} = \frac{260 - 164.5}{\sqrt{82.25}} = 10.5 \quad \text{very large}$$

Therefore: $p \neq q$, hypothesis rejected.

Tools 11-14

	Pos. Rake	Neg. Rake
	freq.	freq.
Greater than -	14	20
Equal	3	4
Less than	8	1
Total	25	25

t-test: Pos. Rake Tools - Distribution of Tools 1-9

$$t = \frac{p_1 - p}{\sqrt{\frac{pq}{n}}}$$

$$t = \frac{\frac{15\frac{1}{2}}{25} - \frac{260}{329}}{\sqrt{\frac{\frac{260}{329} \cdot \frac{69}{329}}{25}}}$$

$t = 2.2$ significant at 5% level for 24 degrees of freedom.

Positive Rake Tools (#12, 14) - Diameter Differences -

+	-
3	5
3	1
2	2
1	1
1	1
1	3
2	1
2	1
+15	3
	1
	1
	1
	3
	2
	- 26

$$\Sigma\Delta = -11$$

$$\bar{x}_{\Delta} = -\frac{11}{25} \qquad \Sigma x^2 = 101$$

$$s^2 = \frac{\Sigma x^2 - (\Sigma x)^2/n}{n}$$

$$s^2 = \frac{101 - (-11/25)^2/25}{25}$$

$$s^2 = 4$$

Negative Rake Tools (#11, 13) - Diameter Difference -

+	-	
6	2	2
+6	4	3
	3	1
	3	1
	3	2
	2	3
	2	3
	2	2
	3	2
		1
		1
		-45

$$\Sigma\Delta = -39$$

$$\bar{x}_{\Delta} = -\frac{39}{25} \qquad \Sigma x^2 = 151$$

$$s^2 = \frac{151 - (-39/25)^2/25}{25}$$

$$s^2 = 6$$

$$F = \frac{s_n^2}{s_p^2} = \frac{6}{4} = 1.5$$

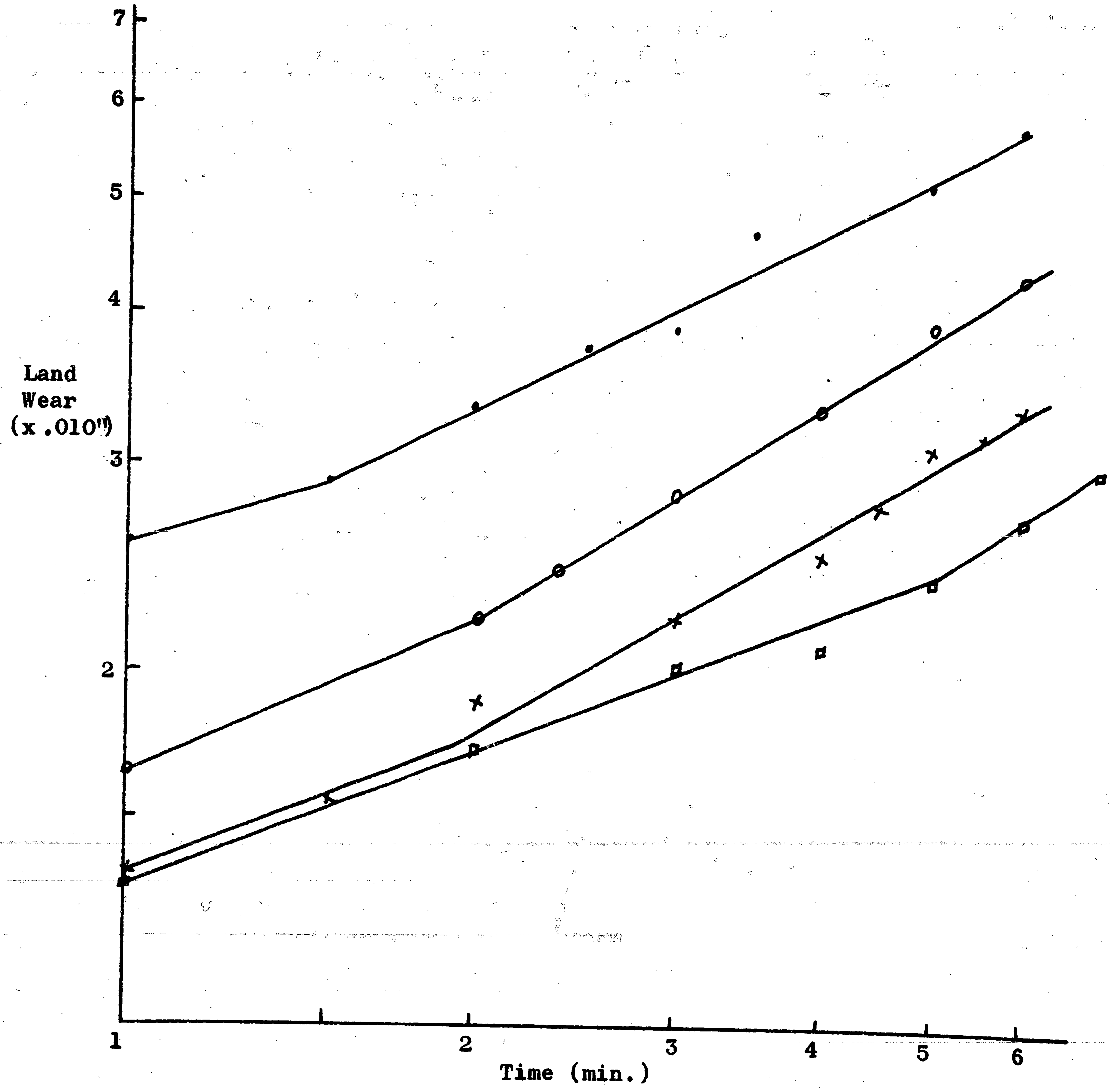
24 and 24 degrees of freedom

Therefore, F - 1.5 is significant at 20% level.

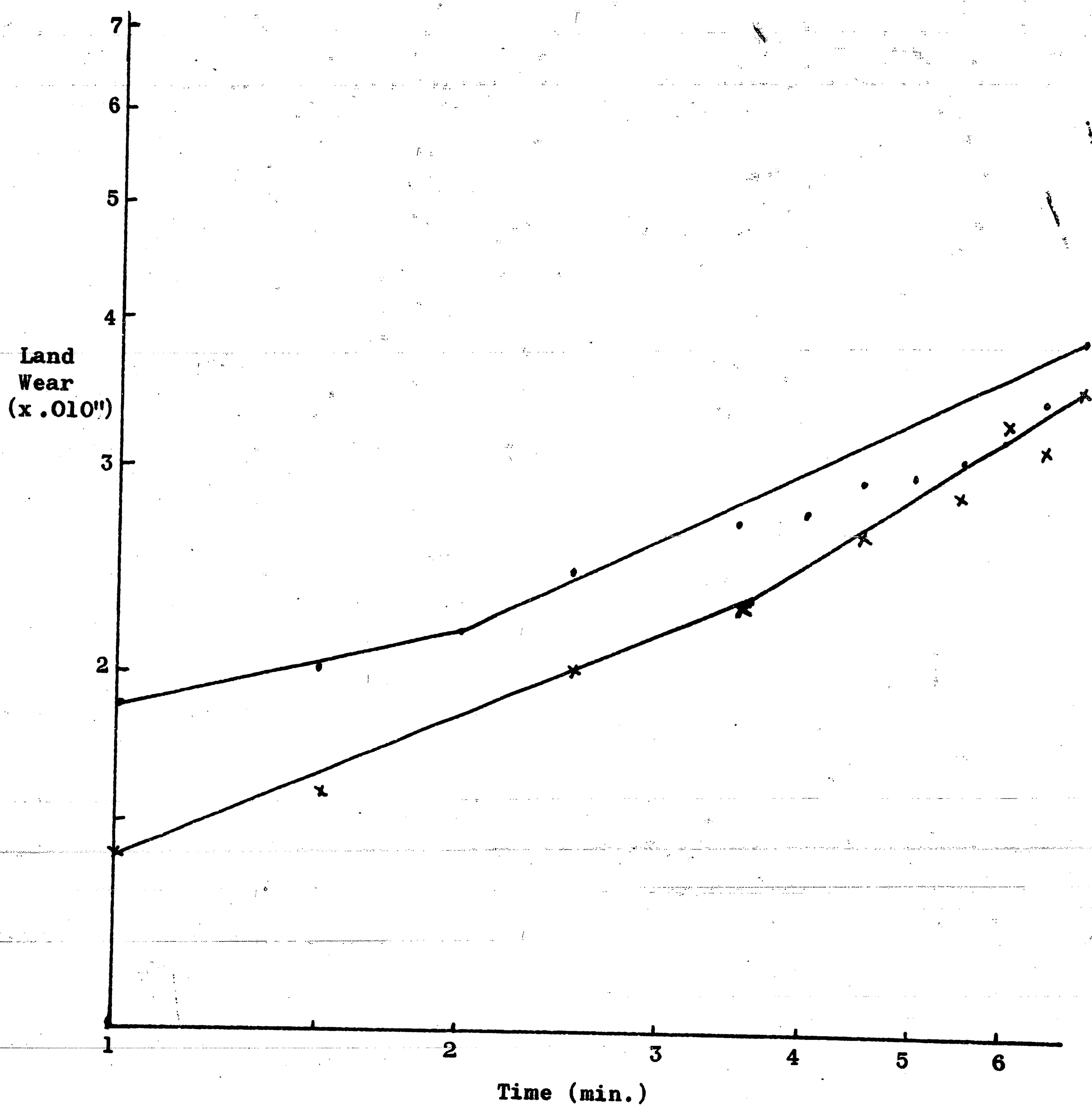
APPENDIX C

Curves for the "Critical Point"

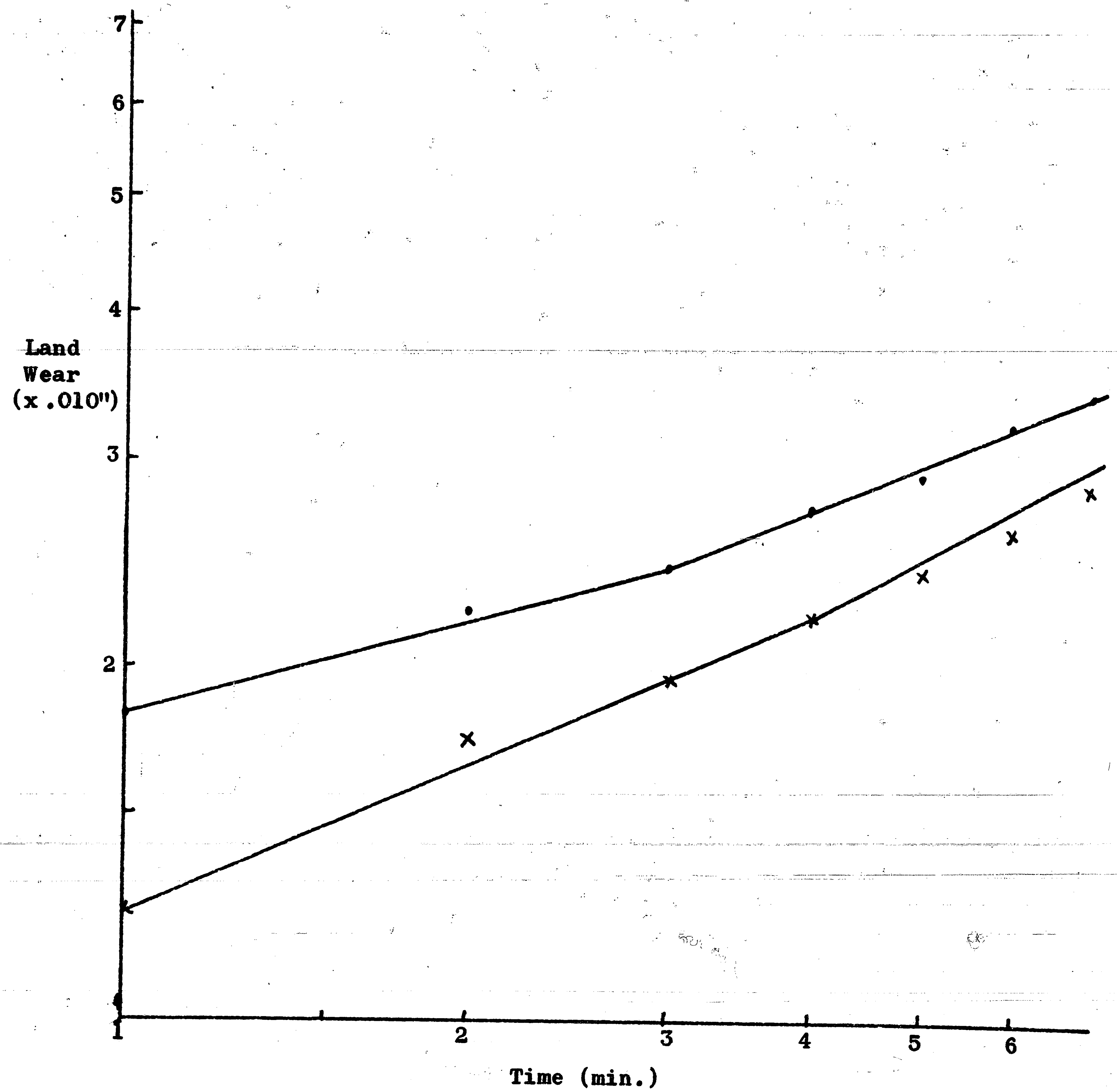
	speed	
Tool #4 (edge 3) •	490 SFPM	Feed - .0168 "/rev.
Tool #8 (edge 1) x	" "	
Tool #1 (edge 5) o	483 "	
Tool #2 (edge 2 ◻	470 "	



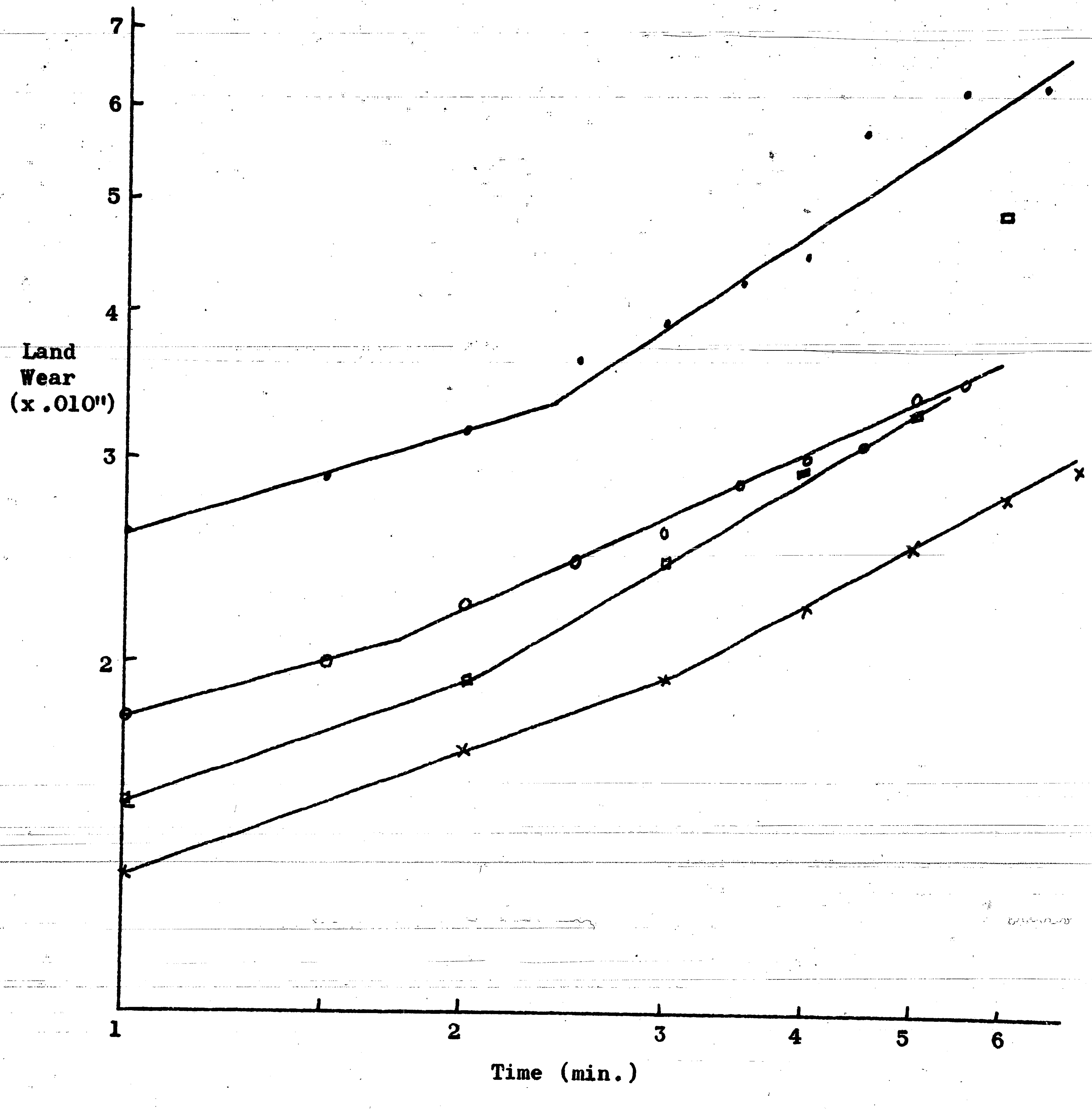
Tool #3 (edge 1) •   425 SFPM   Feed - .0204 "/rev.
Tool #6 (edge 3) x   "   "



Tool #4 (edge 1) • 370 SFPM Feed - .029 "/rev.
Tool #7 (edge 3) x " "



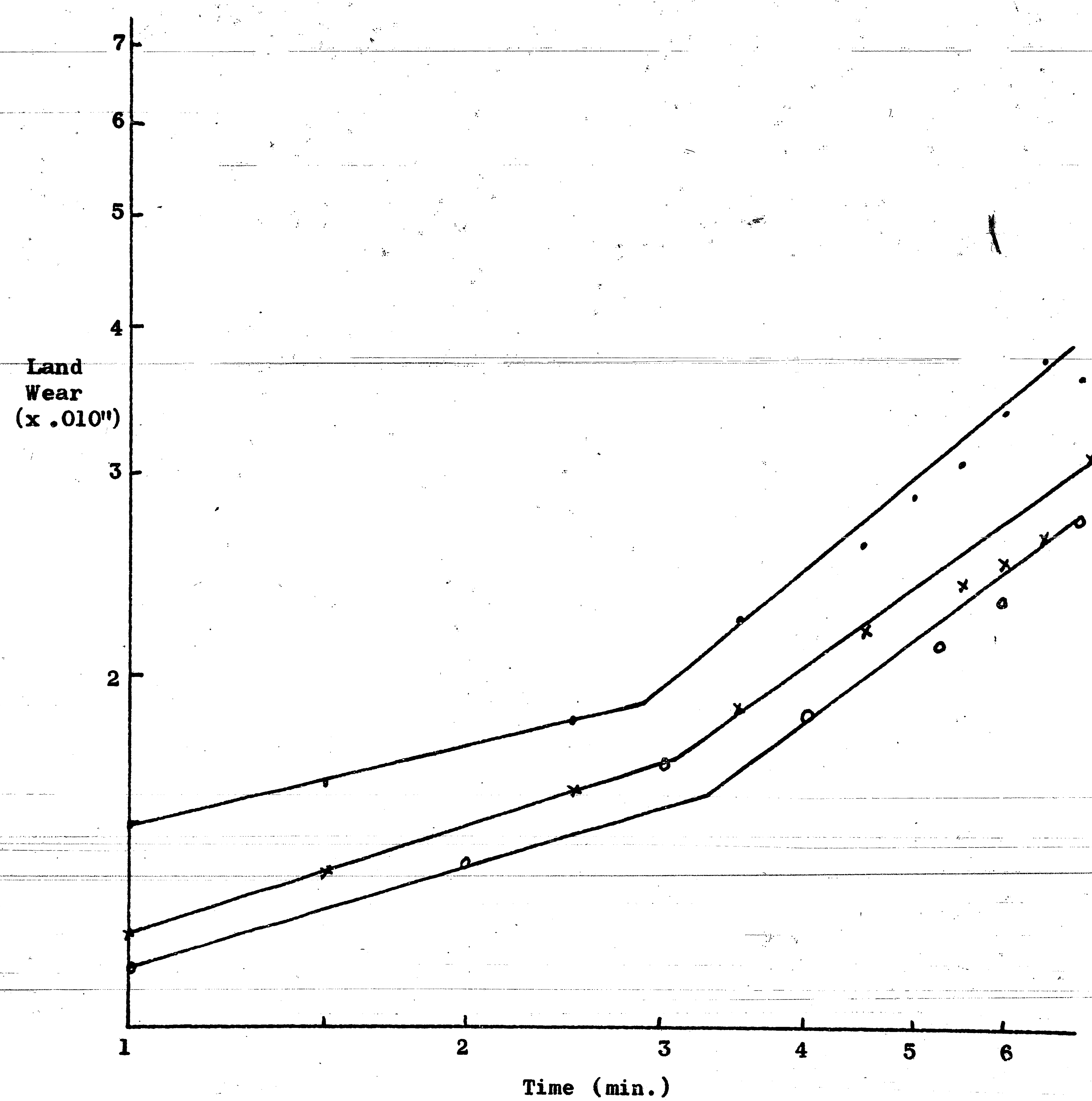
Tool #2 (edge 3) •   454 SFPM   Feed - .0176 "/rev.
Tool #6 (edge 1) x   "   "
Tool #4 (edge 4) o   470 SFPM
Tool #1 (edge 6) ◻   "   "



Tool #4 (edge 2) • 511 SFPM Feed - .0144 "/rev.

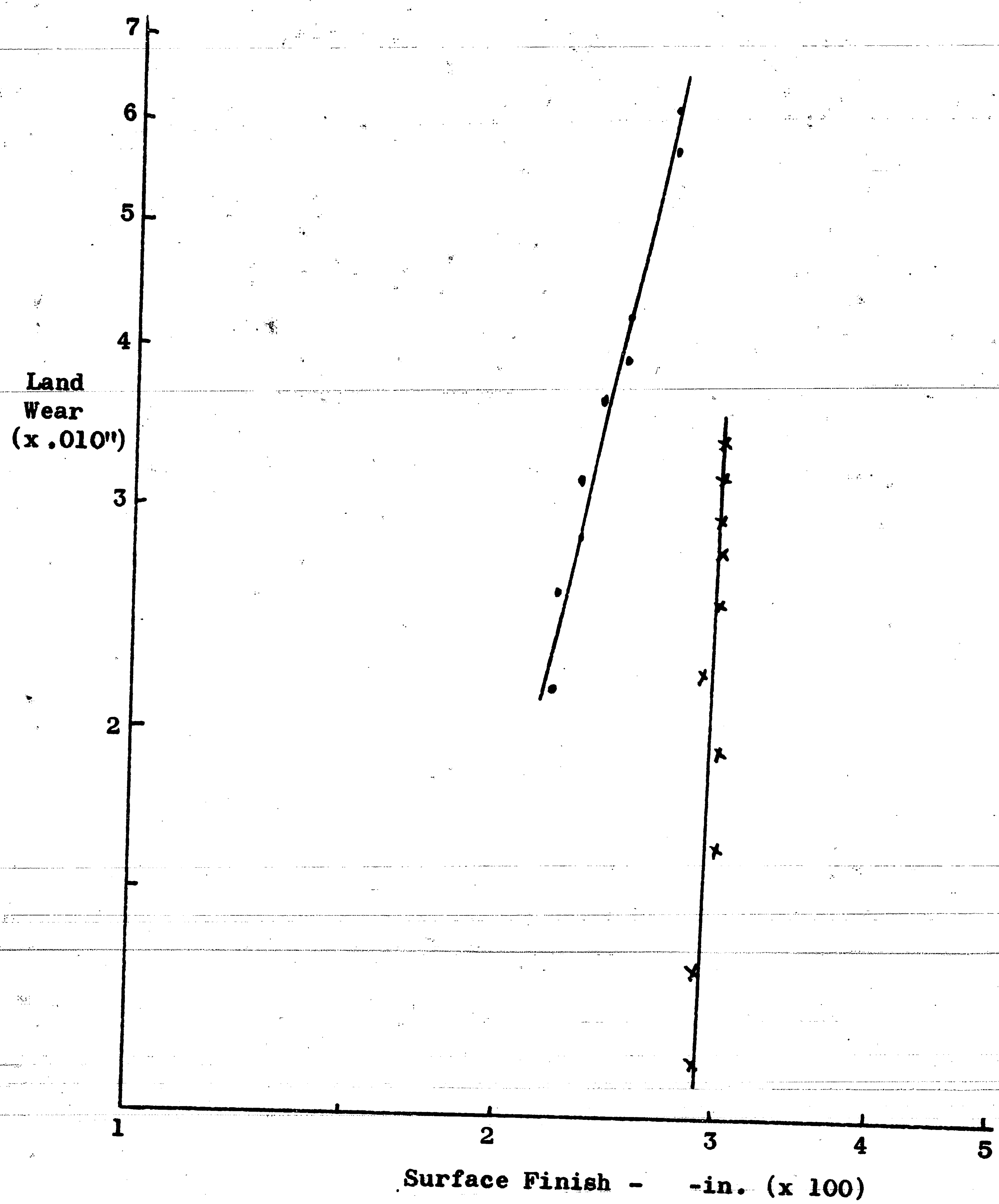
Tool #7 (edge 4) x " "

Tool #5 (edge 4) o 497 "



Surface Finish

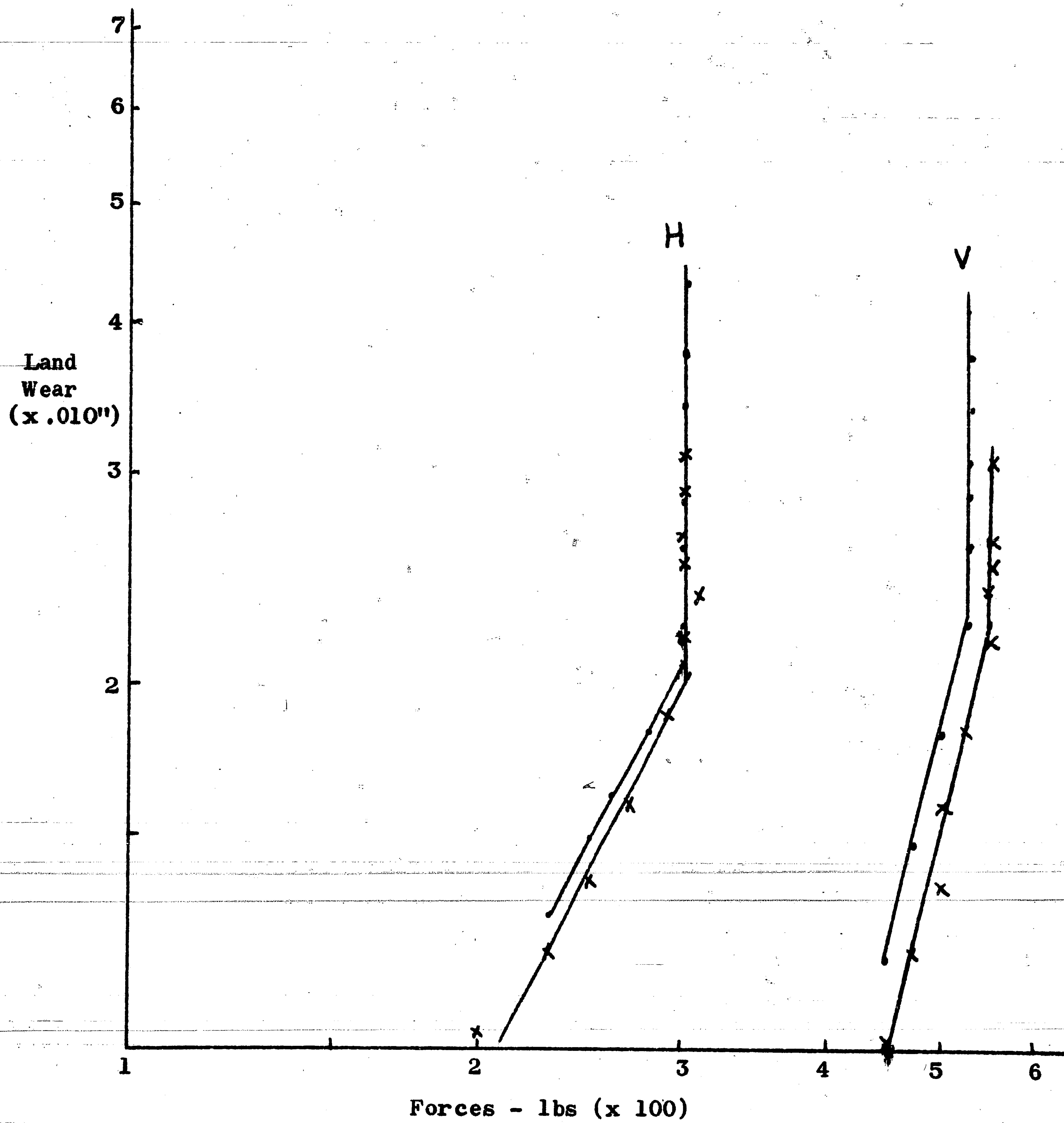
Tool #2 (edge 3) •   454 SFPM   Feed - .0176 "/rev.
Tool #6 (edge 1) x   "   "



Forces

Tool #4 (edge 2) •   511 SFPM   Feed - .0144 "/rev.

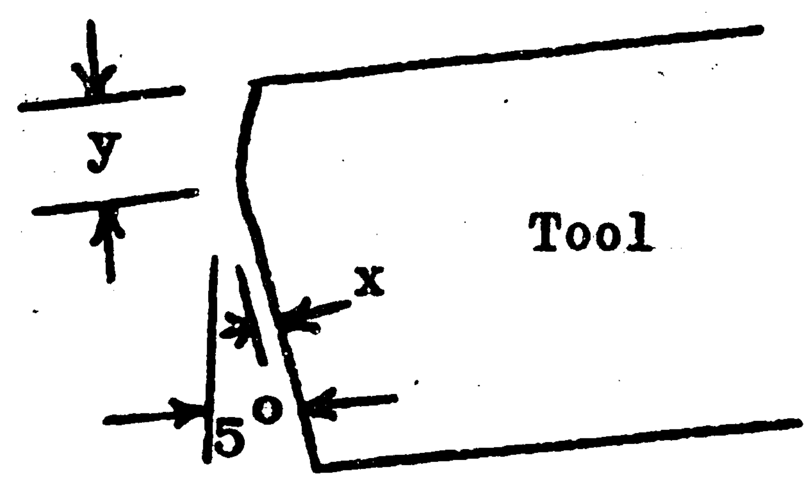
Tool #7 (edge 4) x   "   "



APPENDIX D

Analysis of Plastic Deformation

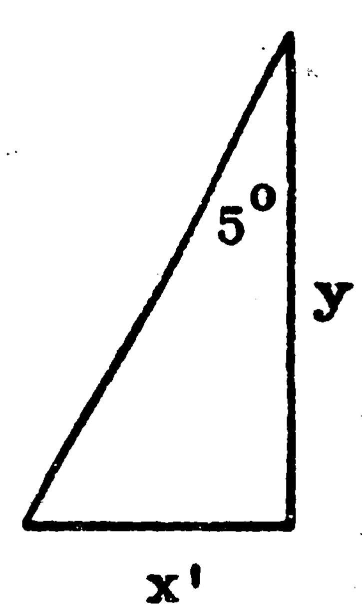
Analysis of Plastic Deformation



Tool #11, edge 2

$x = .004$

$y = .028$



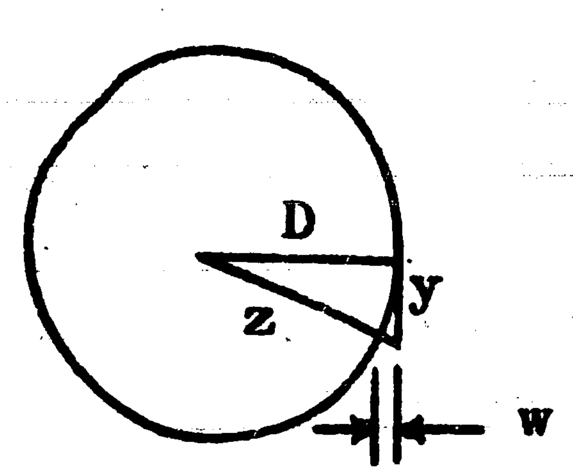
$\tan 5^{\circ} = \frac{x'}{y}$

$.028(\tan 5^{\circ}) = x'$

$x' = .028(.087)$

$x' = .0024$

Work Material



$z^2 = D^2 + y^2$

$z^2 = (4.90)^2 + (.028)^2$

$z = 4.9001$

$w = z - D$

$w = .0001$

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